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WIND SHEAR DETECTION USING MEASUREMENT OF AIRCRAFT TOTAL ENERGY CHANGE

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WIND SHEAR DETECTION USING MEASUREMENT OF AIRCRAFT TOTAL ENERGY CHANGE

Summary

Encounters with wind shears are of concern and have caused major accidents, particularly during landing approaches. Changes in the longitudinal component of the wind affect the aircraft by changing its kinetic energy with respect to the air. It is shown that an instrument which will measure and display the rate of change of total energy of the aircraft with respect to the air will give a leading indication of wind shear problems. This report briefly outlines the concept and discusses some instrumentation and display considerations.

Introduction

A problem arises in the landing approach of an aircraft due to atmospheric disturbances which change the flight path of the airplane. The disturbances of interest here are not properly called turbulence, but are the long period or discrete events such as longitudinal wind shears or downdrafts. Wind shear effects appear first as a change in airspeed followed by an acceleration to a new flight path angle. Recovery requires an adjustment of thrust or power to regain the desired path and airspeed. Because the typical response of the aircraft is slow, often of first order with a time constant of 10 to 20 seconds, displacement from the desired path is detected only after a significant rate of departure is established. If the rate of departure is undetected for more than a few seconds before corrective action is taken, the deviation from the desired flight path may become dangerously large, especially if the aircraft is at low altitude during the final seconds of the approach to landing. There is a need, therefore, for an instrument to provide leading information of a wind shear problem.

In the automatic landing of STOL aircraft the problem of response to atmospheric disturbances is usually more complicated than in CTOL aircraft. Given wind speed changes are a larger percentage of the slow approach speeds, speed control at touchdown and touchdown dispersion are of particular importance for short

runway lengths, strong and often adverse coupling between speed and flight path angle exists, requiring prompt and positive thrust response, and engine response may be slow and may produce more change in vertical speed than in horizontal speed. The coupling of vertical and horizontal speed responses to both horizontal and vertical atmospheric disturbances suggests that information necessary for proper energy management should be combined in a single instrument, and that this instrument should be predictive in nature.

This report presents the results of a brief study of typical aircraft responses to a wind shear. An instrumentation system is proposed using an algorithm designed to display the combined effects of external disturbances on the energy state of the aircraft. The system is described and its application is discussed.

System Description

Analysis and Mechanization

It is proposed that an instrument system be used which detects and displays, to the pilot or automatic flight control system, information about the rate of change of the total energy of the aircraft with respect to the air. Total energy is calculated with respect to the moving air mass because it is the aircraft speed with respect to the air that determines flight path and safety margins. Using the rate of change of the total energy makes the indication predictive.

The specific energy, E, or energy per unit weight, may be written

$$E = h + V^2/2g$$

where h is height above a reference plane

V is speed with respect to the air

g is the acceleration due to gravity.

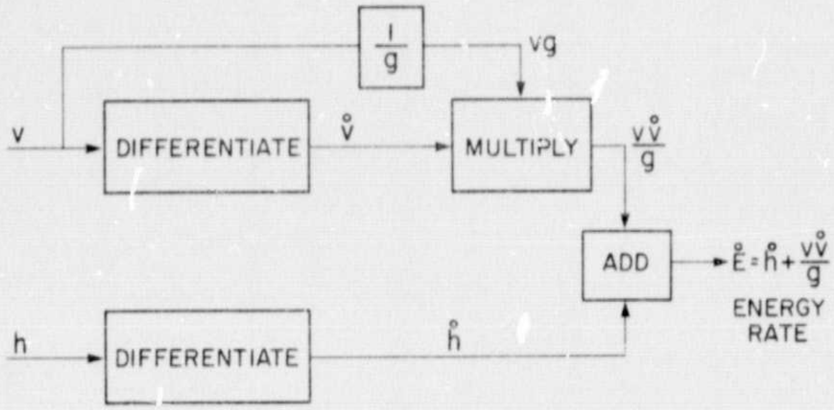
The specific energy has the units of height, and may be called the energy height, h_e .

It is desired to detect and display the rate of change of the energy height.

$$\dot{E} = \dot{h}_e = \dot{h} + \frac{V\dot{V}}{g}$$

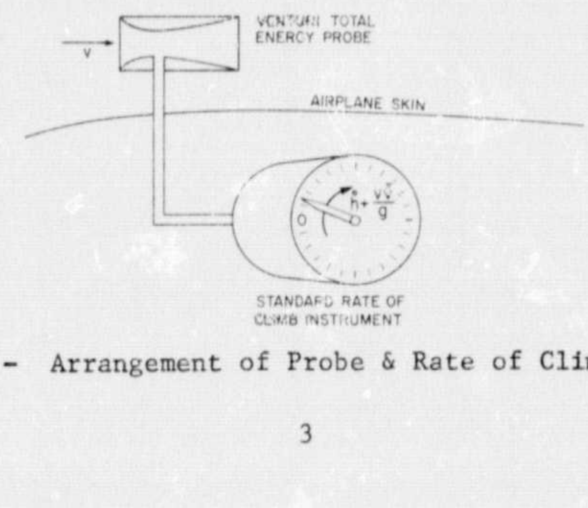
Two methods of doing this are described.

For aircraft which have on-board electronic air data systems the necessary signals are readily mechanized. The block diagram shows how this may be done.



Sketch A - Block Diagram of Energy Rate Computation

For less complex aircraft the signal processing can be done pneumatically with a standard instrument and a special probe. If the probe is designed to provide a signal pressure equal to that at the energy height of the aircraft, a standard rate of climb instrument will take the derivative of that pressure and display it as rate of change of energy height. A probe which has a pressure coefficient of minus one will provide the correct signal pressure source. The appendix gives the derivation and proof.



Sketch B - Arrangement of Probe & Rate of Climb Indicator

Total energy probes of the type described have been used for many years by soaring pilots for the detection of atmospheric energy, primarily because the signal presented is essentially unaffected by the speed and altitude exchanges occuring in maneuvers. It is just this characteristic that is desired here.

Display & Interpretation

Several possibilities for display suggest themselves. For aircraft using the special probe and the rate of climb indicator, it is only required that the instrument be re-labeled "Total Energy Rate Indicator". The display will have the first order lag characteristics of the rate of climb indicator, a time constant of 3 to 6 second

If the energy rate is calculated electrically more possibilities for display present themselves and the dynamics of the instrument might be tailored to optimize response. An auxiliary meter mounted within the flight director instrument is an attractive place where it might be most easily monitored during an approach. A further modification of the signal which might make it more easily interpreted would be to compute the glide angle through the air. This is accomplished by dividing the energy rate by the airspeed. When the airspeed is constant, this result is simply the present value of the air flight path angle. During the onset of a wind gradient the kinetic energy rate term adds an increment to predict the final value of the glide angle through the air. A change in thrust or drag due to a configuration change will be reflected in the same way in the energy rate and in predicted glide angle.

The electronic attitude director-indicator offers many possibilities for displaying the energy rate or predicted air flight path angle.

In interpreting the indications of the Total Energy Rate Indicator the pilot must recognize that changes can only be caused by external disturbances or by changes in thrust or drag due to his own manipulation of configuration or throttle. Maneuvers due to flight controls operation will ideally produce zero changes because longitudinal motions proceed by exchanging speed and

altitude at constant energy. The classical Phugoid maneuver is an example. Therefore, any undesired variation in the energy rate is to be interpreted as a longitudinal gust or vertical draft, and should be followed by an appropriate thrust adjustment.

Results & Discussion

In order to show the response of typical aircraft to wind shear encounters, and the responses of standard as well as the proposed instruments, example calculations were made. Two examples were chosen. The first is the NASA Augmentor Wing Jet STOL Research Aircraft and the second is a large jet transport. To simplify the analysis it is assumed that both aircraft are flown with pitch attitude tightly controlled by either automatic pilot or human pilot, but no other longitudinal control is used. The aircraft are initially on a stabilized approach at a velocity of 111 kph (60 KT) and a flight path angle of -7.5 degrees for the STOL, and 267 kph (144 KT) and -3 degrees for the jet. Both are assumed to encounter a decreasing headwind gradient. For ease in analysis the gradient is expressed as a function of time, calculated to represent a spatial gradient of .486kph/m (8 kt/100 ft) at the initial descent rate of the example aircraft. For the STOL aircraft the gradient is .546 m/s/s and for the large jet transport the gradient encountered is .527 m/s/s. The wind speed gradient is shown in the top part of Figures 1 and 2. The figures also show the resulting perturbations in speed, flight path angle, and deviation from glide slope.

It is observed from the figures that the first response to the onset of the wind gradient is a loss of airspeed which reduces lift and initiates a change in the flight path angle. The new flight path produces an acceleration in the inertial speed and a deviation in height from the initial glide slope. These responses are characterized by first order lags of about 8 seconds for the STOL aircraft and about 19 seconds for the jet transport.

The wind gradient, a ramp function in time, is a step function in rate of change of energy. The lower part of the figures show how this step function

in energy rate is modified by the aircraft motion, as well as the response of an energy rate instrument having a time response characterized by a first order filter of 4 seconds time constant. A comparison is made with the rate of change of geometric height and the indication of a rate of climb indicator also having a 4 second lag. It will be seen that the energy rate indication leads flight path deviations rather than lagging them, and gives the controller, human or automatic, an advance indication of the expected final state.

An example of the potential usefulness of the energy rate concept may be taken from Reference 1. Data was analyzed from a recent landing approach accident of a jet transport to John F. Kennedy Airport during very turbulent conditions including strong wind shear. The results (Figure 3) show the indicated rate of descent during the last 300 meters, and superimposed on that is a plot of the energy rate calculated with a 4-second lag. The presence of strong turbulence is indicated by the rapid fluctuations of the energy rate, especially at the higher altitudes. At about 100 meters a strong wind shear is encountered and the energy rate shows a large and sustained excursion. The energy rate is seen to give a lead indication over that available from a standard rate of climb indicator.

The concepts presented have encouraged the initiation of some experimental work. A total energy probe has been mounted on a light airplane and connected to a rate of climb indicator for a qualitative evaluation of energy rate display. Wind gradients near the ground are clearly shown when the energy rate instrument is compared with the standard rate of climb instrument. Further experiments are recommended using more sophisticated displays such as the Electronic Attitude Director-Indicator. Methods for using the energy rate indications in normal approaches should be explored and developed to insure that the indications of wind shear will be detected in the normal instrument scan.

Conclusions

A concept of a flight energy instrument system has been presented in which the rate of change of total energy with respect to the air is used to give a predictive indication of changes in descent rate due to atmospheric disturbances such as wind shears.

The concept may be implemented using a special total energy probe or by simple computations using on-board air data systems.

The output of the device may be displayed on a Total Energy Rate Indicator, in a flight director or in an Electronic Attitude Director-Indicator, and it may be used as an input to the automatic flight control system. The output gives leading indications of descent rate or air flight path angle in response to wind shears.

Preliminary experiments support a recommendation for further research in flight and simulation.

APPENDIX

Determination of Energy Height

Energy height is defined as the altitude which could be reached if all the kinetic energy were converted to potential energy.

$$h_e = h + V^2/2g$$

where h_e = energy height

h = height above a reference surface

V = speed

g = acceleration due to gravity

The altitude h is measured indirectly by measuring the ambient pressure. The energy height could be measured in the same way if a pressure could be identified which would be equal to the ambient pressure reduced by an amount corresponding to the kinetic energy term in the equation.

The change in height due to the kinetic energy term is

$$\Delta he = V^2/2g$$

The change in pressure corresponding to that change in height may be found from the atmospheric balance equation

$$\Delta p = -g\rho\Delta h$$

where the air density ρ may be assumed constant over the height change Δh. Upon substitution pressure change is found to be

$$\Delta p = -\frac{\rho V^2}{2}$$

This is recognized as the negative of the dynamic pressure. The pressure coefficient Cp is defined as

$$Cp = \frac{2\Delta p}{\rho V^2}$$

where $\Delta p = p - p_s$

p = local pressure

p_s = ambient static pressure

The required condition will be met if $Cp = -1$. This can be accomplished in an ideal venturi tube having an exit area $\sqrt{\text{two}}$ times the throat area, provided that the venturi is located out of boundary layer and propeller slipstream, and in a region where the static pressure coefficient is zero.

References

1. Wingrove, Rodney C. "Analysis of Wind Profiles From the Accident at John F. Kennedy Airport, June 24, 1975," NASA TMX 73,122, April 1976.

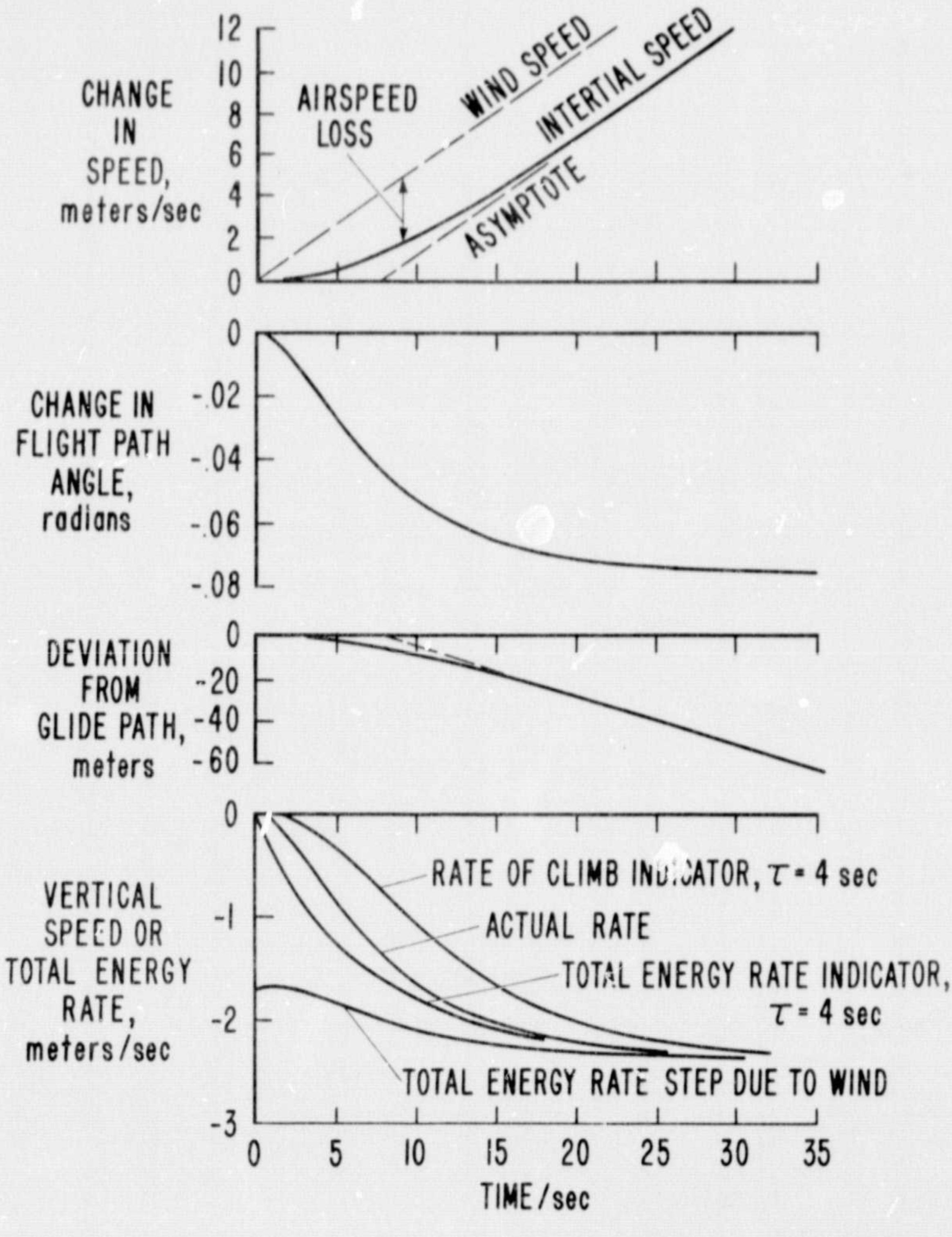


Fig. 1 Response of Augmentor Wing Jet STOL Research Aircraft to a Ramp Wind Shear.

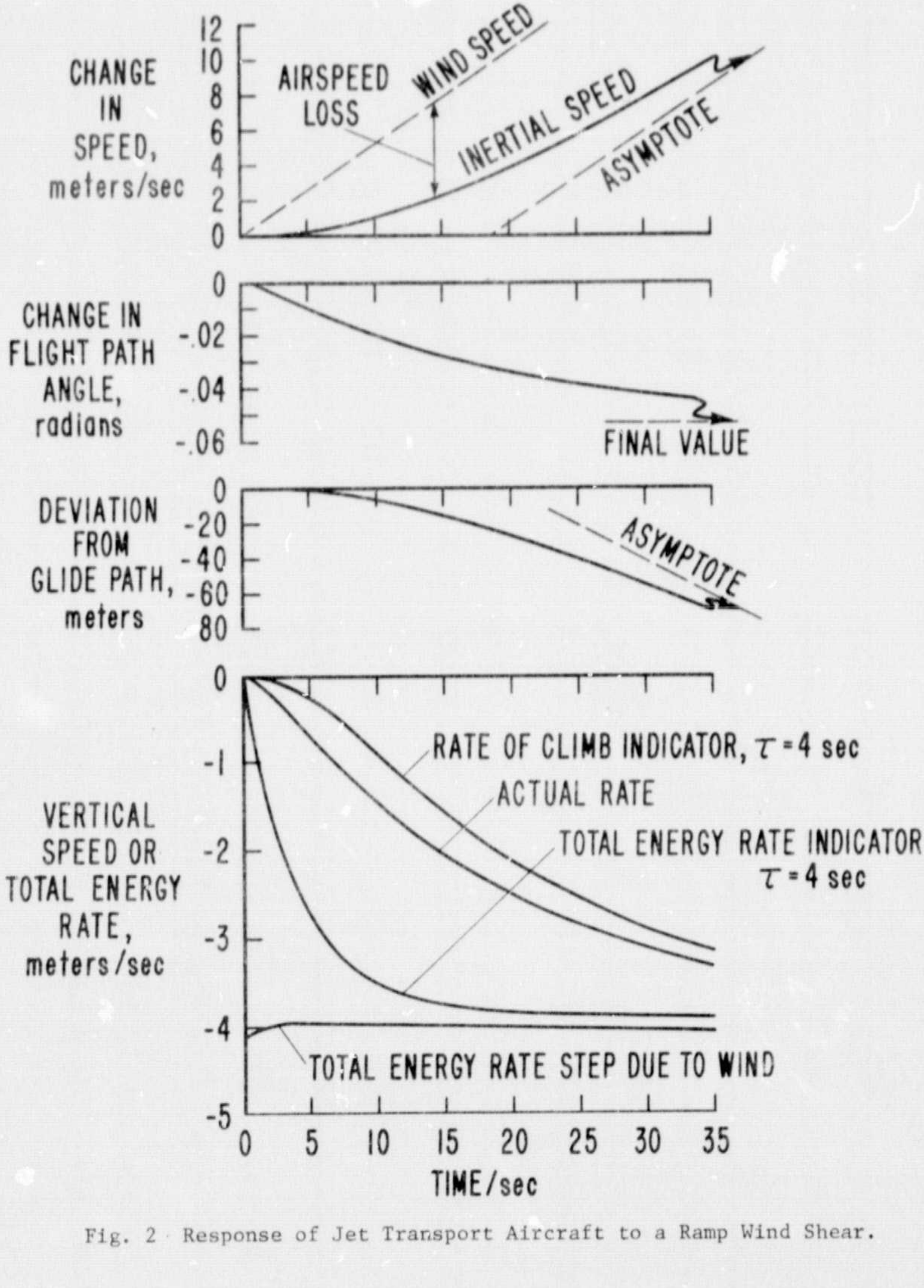


Fig. 2 Response of Jet Transport Aircraft to a Ramp Wind Shear.

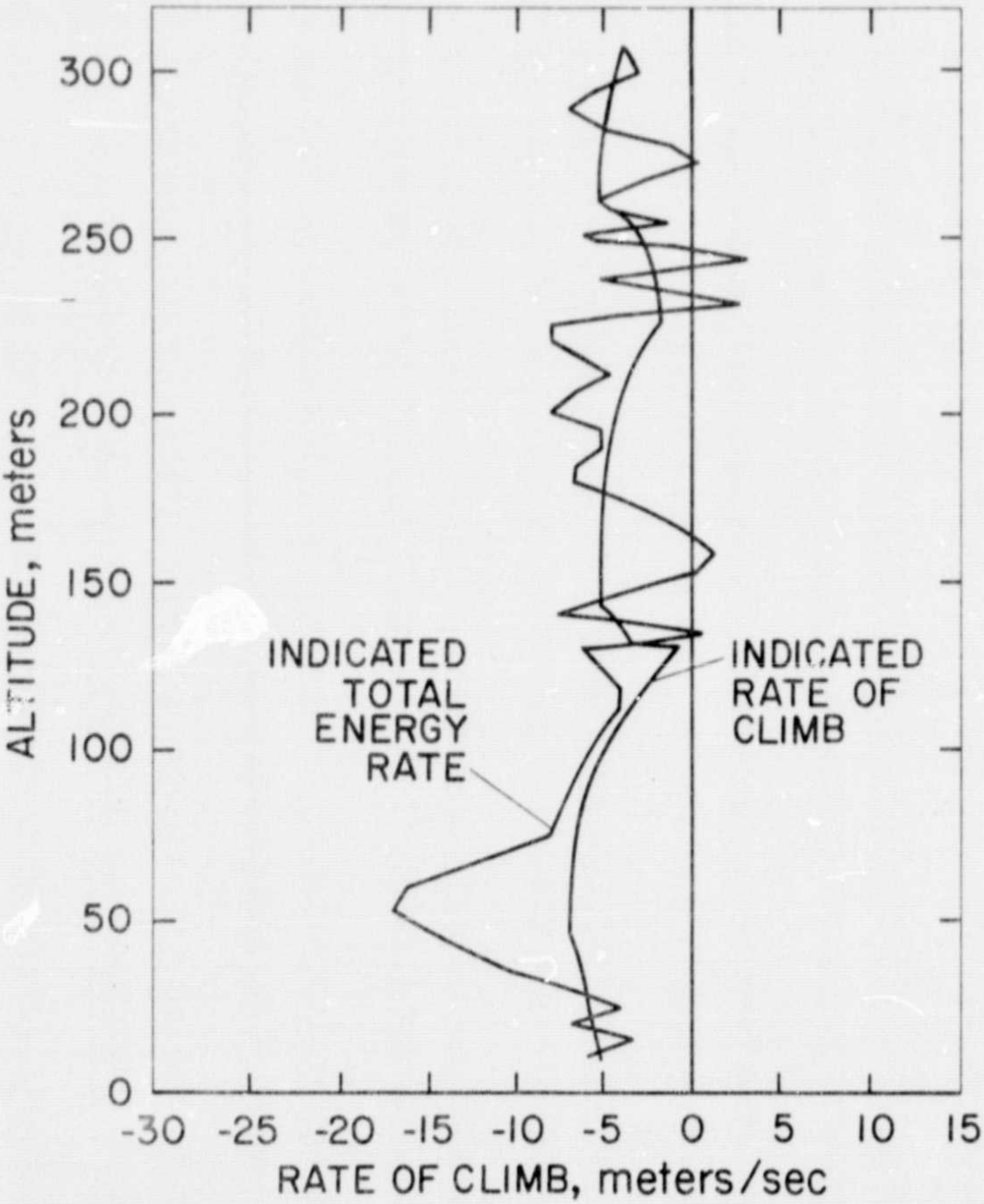


Fig. 3 Derived From the Jet Landing Approach Accident at JFK Airport, June 24, 1975.